Performance Analysis of ITS-G5 for Smart Train Composition Coupling

1st Arrate Alonso Gómez
Electronics and Computer Science Dept.
Mondragon Unibertsitatea
Arrasate-Mondragon, Spain
aalonso@mondragon.edu

2nd Erislandy Mozo
Electronics and Computer Science Dept.
Mondragon Unibertsitatea
Arrasate-Mondragon, Spain
emozo@mondragon.edu

3rd Laura Bernadó
Center for Digital Safety & Security
Austrian Institute of Technology GmbH
Vienna, Austria
laura.bernado@ait.ac.at

4th Stefan Zelenbaba
Center for Digital Safety & Security
Austrian Institute of Technology GmbH
Vienna, Austria
stefan.zelenbaba@ait.ac.at

5th Thomas Zemen
Center for Digital Safety & Security
Austrian Institute of Technology GmbH
Vienna, Austria
thomas.zemen@ait.ac.at

6th Francisco Parrilla
Transportation
Indra
Madrid, Spain
fparrilla@indra.es

7th Adrián Alberdi
Transportation
Indra
Madrid, Spain
aalberdi@indra.es

***Abstract*—In this paper we present first measurement results the use of ITS-G5 technology for Smart Train Composition Coupling. Intelligent Transport System (ITS-G5) communication link has been already use for Train-to-Train (T2T) communications. The SCOTT(Secure COnnected Trustable Things) project focuses on Vehicle to Vehicle (V2V) communications as one of the main development lines in the Smart Train Coupling Composition (STCC) use case and additionally in Vehicle to Infrastructure bidirectional (V2I/I2V) communications as one of the main development lines in the Trustable Warning System (TWS) for critical Areas use case. The V2V communications development in the SCOTT project focuses on the decentralization of the communications in order to make low latency highly reliable communications between moving train composition. These use cases will end with the demonstration of a Virtual Coupling system relying on these decentralized V2V communications. This system increases the capacity of the railway lines all over the world by allowing train compositions to drive closer to each other in a safe manner. The investigated measurement categories are channel characteristics, system performance and environmental aspects.**

***Index Terms*—Railway wireless communications, traffic safety, traffic efficiency, time-critical applications, smart train composition**

I. Introduction

The European Union, through the transportation commission (DG Move), defined several objectives to be solved in order to position the a European transportation technology at the world top. The objectives are

- to double the rail capacity,
- to reduce of CAPEX and OPEX by as much as 50%, and
- to enhance the overall reliability (by as much as 50%), safety and security.

The current solutions cannot solve these objectives; cabled solutions and the currently deployed GSM-R solution are a bottleneck that cannot be avoided. The cost of the core of the current communications networks (GSM-R, cabled) makes also difficult to reduce the CAPEX/OPEX costs up to 50%.

In order to accomplish these objectives the paradigm must be completely switched. To solve this the rail domain of the SCOTT project proposes a change on the communication standards. The use of decentralized, distributed and open standards is the new solution proposed. IEEE802.11p/ITS-G5 provides this *reliable* framework but still it must be adapted to some specific needs of the rail domain. This standard offers the flexibility to be modified for Communication Based Train Control (CBTC). As stated in [1], better performances could be achieved by adjusting various parameters. This adjustments to the railway propagation scenario and railway communication needs, will then finally lead to IEEE802.11p/ITS-G5 Railway. Additionally, alternative designs and topologies for the train-to-track side radio network also hold the key to providing high *availability* in CBTC, and the availability can be increased dramatically by ensuring redundancy at multiple levels. These communication solutions, are to be used for safety critical operation. This fact forces every layer in the communication stack to be *secure*. For rail system operator, RAMS (Reliable Available Maintainable and Secure) means a safe, reliable, high-quality service and lower operating and maintenance costs. For the rail system provider, RAMS is representing a high-quality system and product.

The SCOTT project aims at two main V2X communication scenarios: Vehicle to Vehicle (V2V) communications as one of the main development lines in the Smart Train Coupling Composition (STCC) use case and Vehicle to Infrastructure bidirectional (V2I/I2V) communications as one of the main development lines in the Trustable Warning System (TWS) for critical Areas use case. The **V2V communications development** fixates on the decentralization of the communications in order to enable low latency highly reliable communications between moving trains. This use case will end with the demonstration of a Virtual Coupling system relying on these decentralized

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V2V communications. This system increases the capacity of the railway lines all over the world by allowing trains to drive closer to each other in a safe manner. The **V2I/I2V communication development** covers two very distinct needs. In the TWS for critical areas, the communications are used to connect the train with the critical areas in a safe manner in order to decide the trains conduction. The second need is the interconnection of different Wireless Sensor Networks (WSN) deployed on the track-side (with very constrained resources) with the systems built on the train consists. This exemplifies the need for distributed communication systems built on commercial products with cost effectiveness in mind.

II. State of Railway Communication Technologies

Several research projects have been carried out to modernize the railway communication infrastructure in recent years. The so-called Train-to-Train (T2T) communications allows a reliable radio link that is capable of transferring data directly between trains, and this additional wireless communication channel is created along with the T2I (Train-to-Infrastructure) link already available. This T2T link can handle critical time events much better than a centralized system. This way trains can exchange information about their composition, position, power controls, relative speed and train length among others. Currently, commercial technologies such as LTE, TETRA, WIFI and WiMAX have capabilities to support T2T links. In this section first an overview of the new time-critical applications is provided, then the T2T connectivity tests carried out in various conditions and environments are outlined, thirdly different propagation channel models are studied, and finally the performance under high speed conditions are examined.

T2T communications are foreseen as the enablers of new time-critical applications, which will allow to improve train safety, availability and operation. Critical applications such as collision evasion systems, decentralized CBTC and train composition coupling are under investigation. In [2], the German Aerospace Center (DLR) presents a Railway Collision Avoidance System (RCAS) based on the TETRA system, which allows the driver to have an accurate knowledge of the state of movement of trains in vicinity without the help of equipment on ground (i.e. T2I) and he/she can make decisions in the face of dangerous situations. In [3] a decentralized CBTC system is modeled, in which the functions of the equipment on ground are transferred to the train, increasing its autonomy. This control philosophy was implemented by Alstom in [4] and it is able to double the capacity of the track, reduce the separation between trains to 66 seconds and reduce the number of equipment on ground by 20%. Finally, the idea of composition coupling between trains was initially presented in [5], where the trains can autonomously form convoys optimizing their operation and decreasing the separation between trains beyond the braking distance. Unlike the rest of the applications aforementioned, to the authors knowledge there is no practical implementation of composition coupling, much engineering work and research is needed.

In relation to the evaluation of the performance of different commercial technologies, in [7] the results of a measurement campaign are presented in the T2T environment with ITS-G5, a train and a vehicle are used, both equipped with IEEE 802.11p Cohda devices on channels 180 and 176. The delay of adaptation, received power, distance between trains and relative speed are estimated. The results show that an increase in transmission power improves the adaptation delay. While in [8] the results of the ITS-G5 T2T measurements campaign are shown for HSR (High Speed Railway) typical scenarios. Effects of the environment and the influence of the train speed are investigated. In rural environments, a stable connection was established up to 1.2 km. For tunnels and big buildings as in urban environments a higher link distance up to 2.2 km could be achieved because of wave guiding effects.

In [9] a T2T communication model is proposed at the level of the physical layer with an OFDM-MIMO system based on multi-hop cooperation. The BER (Bit Error Rate) expression is determined analytically and calculated for several SNR (Signal and Noise Power Relationship) values. The results show that the BER is decremented to 10^{-6} when the SNR is 10 dB and that the minimum received power is -84 dBm. In [10] a communication system based on the ITS-G5 standard for an Intra-Train link is investigated, analyzing the influence on the propagation channel on the internal and external environment of the train, for different distances and speeds. The results show that the multi-hop communication operation can significantly improve the PER (Packet Error Rate) and the transmission distance in Intra-Train communications. While in [11] the propagation conditions of the T2T communications are evaluated, enabled by TETRA technology in the 450 MHz band. Short data service packets (SDS) of 33 bytes are transmitted, an EIRP of 40 dBm and two Frecciarossa ETR 500 trains are used with speeds of up to 300 km/m. A transmission range of 40 km is obtained and several manoeuvres are carried out according to the composition coupling paradigm. In [12] is extended the work in [7] and the MER (Message Erasure Rate) is analyzed according to the separation between the trains. Furthermore, it was found that the relative speed of the train does not have an appreciable influence on the MER, even at relative speeds above 400 Km/h. In [13] a geometry-based stochastic modeling (GBSCM) model is presented for a viaduct T2T environment in the 900 MHz band. The wireless channel is characterized with the propagation loss, the root mean square of the delay spread (RMS-DS), the K factor and the covariate of the envelope. The results show that the distribution of Weibull and Ricean are two well-suited distributions for the K factor.

In [14] is presented an analysis of ITS-G5 as T2T link under HSR conditions. The performance at open field environment and tunnels at high speed were investigated in detail. For both environments, log-distance models were derived and the parameters presented. The results show that deep fades can be observed for link distances above 200 m in open field and above 500 m in tunnels. Nevertheless, stable links could be achieved for distances up to 2 km. The high speed (greater than

200 km/h) has no significant effect on the data transmission. In [2], [15] the propagation conditions of the T2T channel in the 470 MHz band is investigated under various scenarios (urban, suburban, tunnel and rural areas). The Doppler spectrum and frequency are analyzed and the Hata-Okumura model is used to model the propagation losses in the different scenarios. The results show that the line of sight condition in the analyzed scenarios is typically maintained around 100 meters.

III. SCOTT RAILWAY COMMUNICATION PLATFORM

SCOTT project has defined a three-layer architecture for the communications across the different systems, which has AIOTI and ITU reference architectures as inspiration. Its application to the railway domain is to be seen in Fig. 1. This development has been performed considering interoperability across different domains. This paper investigates communication technologies servicing systems in the Level 1 (L1) of the architecture. This level covers the decentralized communications among gathering gateways.

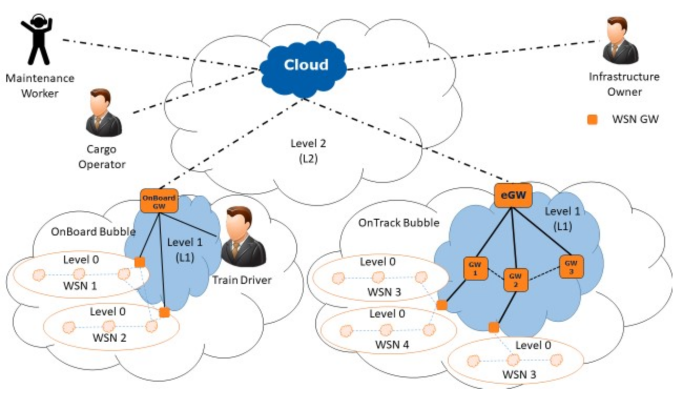

Fig. 1. Layered architecture.

This architecture is applied seamlessly to the three use cases from the two aforementioned V2X communication scenarios:

1) Virtual Coupling use case
2) TWS for critical areas use case, and
3) V2I applied to IoT devices.

How these connections interact with each other and are located is represented in Fig. 2.

The architecture was envisioned in the context of a service-driven communications architecture. The services running in the upper layers rely on the transparent usage of heterogeneous lower stack layers. A service running in the OSI level 5 will fully rely on the correct functioning of all the lower OSI levels. In the L1 communications the following communications stack will be used:

- IEEE802.11p-railway
- IP
- TCP+TLS
- Railway Safe Transport Application (RaSTA) with MQTT/AMQP

This is the stack proposed for the rail domain demonstrator inside the SCOTT project. On top of this stack, a data ontology

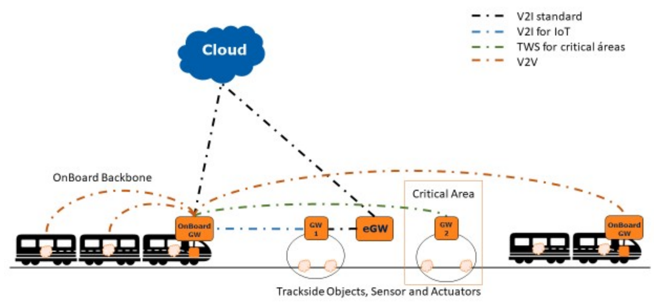

Fig. 2. Physical representation of the SCOTT architecture for the Rail domain.

based in services will be instantiated. This ontology will carry the information related to the services. Taking this stack as an example the differentiation in a multi-tier architecture, as understood in Systems Engineering, can be easily seen. It should also be noted that some services are running in safety critical conditions (a problem in the system could be fatal). This forces the system to be deeply analyzed in order to provide a high safety level throughout the stack.

A. Data Access Layer

In SCOTT Railway two **V2X communication scenarios** are considered. Hence a communication link needs to be either established between two trains or between a train and a stationary station near the rail track. This T2X communication link must fulfill high safety and security requirements while the trains are moving at high velocity. Such wireless communication channels are subject to multipath propagation causing delay and Doppler dispersion that change over time [16], i.e. non-stationary propagation conditions. As aforementioned, this reliable radio link, capable of transferring data directly between trains, is created along with the T2I link already available. This T2T link can handle critical time events much better than a centralized system. Still, the T2I low-latency wireless communication link contributes to the real-time control loop, and shall ensure that break commands of the following train are initiated in time.

Currently the most widely used solution is a T2I. GSM-R, is the most popular wireless communication standard for high-speed trains. Work is ongoing to replace the aging GMS-R standard with LTE-R [17]. However, it is expected that LTE-R would also have troubles to fulfill the millisecond latency requirements for reliable virtual train coupling. Hence the need of a T2T solution (without base-station) arises. This could be realized by a WLAN like system like IEEE 802.11p/ITS-G5. The drawback of IEEE 802.11p is its bad performance in non line-of-sight situations with velocities above 50km/h. But as mentioned in [1], its performance can enhance adapting the parametrization values of the standard to the new communication scenario and also considering new network architectures.

For the smart train composition service a T2T link is required and thus SCOTT project considers an adapted IEEE802.11p/ITS-G5 for providing this reliable communication. Additionally, a backward compatible modification of the 11p pilot pattern by adding a post-amble at the end of the data frame and an iterative channel estimation method could be considered, as discussed in [19], [20]. Though, these latter methods require a channel estimator with increased complexity.

For services that require a LTI link (i.e. longer-range communications), a promising data access layer for high speed train is the ultra-reliable low-latency communication (URLLC) mode of 5G systems being currently investigated and developed [21]. Although, here the availability is still some years in the future with products expected for 2021-2022. Earlier, LTE vehicular chips will be available that add a device-to-device communication mode to LTE via the PC5 physical (PHY) layer. The PC5 link provides enough pilot symbols for robust channel estimation in doubly dispersive high-speed train channels [22]. The drawback of PC5 is the fact that it works at 5.9 GHz, and its waveform is not compatible with the power masks, and hence it cannot coexists with other systems currently operating on the same frequency band. Additionally, as stated in [28], in the absence of a network, PC5 significantly suffers due to the choice of maintaining the same symbol structure and similar frame structure as in LTE. IEEE802.11p is better in terms of robustness and efficiency. In the presence of a network, LTE-V2X can leverage the years of innovations in the cellular domain providing a valid alternative for V2I and I2V services. IEEE802.11p covers V2I and I2V as well, but in a less efficient way.

The hybrid T2X approach can combine the advantages of each technology to generate a more complete and promising solution. For example, IEEE802.11p is more robust to safety messages than LTE-V2X. On the other hand, the cellular network provides longer-range connectivity between vehicles and between vehicles and the cloud. SCOTT project will also consider this possibility.

B. Business Layer

SCOTT project has a service-oriented business layer. This services information will be arranged following the rail domain ontology, which is based on a queue structure to be used following the MQTT/AMQP scheme.

For the measurement campaign concerning this paper, the following physical constraints are envisioned. The VC service will need to communicate two moving entities traveling at speeds up to 350 km/h and at a distance greater than 300 m.

C. Application Layer

The application layer is the highest level of abstraction in the multi-tier architecture. In this layer, the presentation of the services to the final consumer/client is analyzed. The services provided in this tier may use one or multiple parts of the business layer simultaneously. These services will be offered to clients together with the full architecture in order to be used in the railway domain.

IV. Measurement Campaign

In order to evaluate and analyze relevant parameters for T2T communication links, a measurement campaign is necessary pursuing two goals: channel sounding and connectivity tests. These two operations will be carried out simultaneously using two frequency bands, both close to 5.9 GHz, but separated enough to avoid interferences.

A. Equipment

1) Channel Sounding: The measurements are conducted using the AIT channel sounder which uses on universal software radio peripheral (USRP) Software Defined Radio (SDR) reconfigurable hardware [23], shown in Fig. 3.

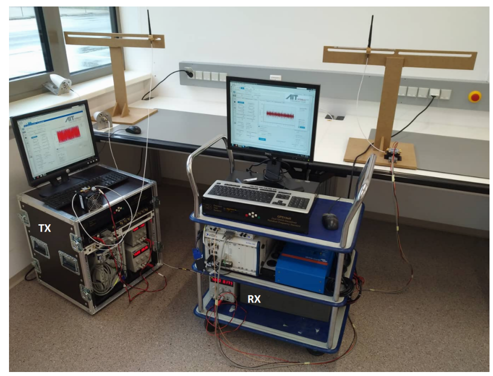

Fig. 3. AIT Channel Sounder.

The transmitter (TX) node of the sounder sends out optimized sounding signals with a low crest factor in a periodical manner [23]. The sounding sequence is repeated three times for one sounding period of 13 μs, and followed by a guard period to allow buffer clearing and to avoid interference to the next sounding period. Both nodes of the sounder are synced to a pulse per second (PPS) signal provided by a GPS disciplined rubidium oscillator, as well as the 10 MHz frequency reference signal. The receiver (RX) records the raw received signal and displays the channel transfer function $\mathrm{H}(t, f)$ or the channel impulse response $\mathrm{h}(t, \tau)$ in real-time to enable live data evaluation.

A bandwidth of 150 MHz is selected for the measurements, at the 5.8 GHz carrier frequency. This frequency was chosen such that it complies with the ISM frequency band limits, and it is still close enough to the 5.9 GHz band meant for 802.11p. A transmit power of 27 dBm is selected, while automatic gain control is implemented on the receiver side. One antenna at the TX and the RX side is considered respectively, hence, single-input single-output measurements (SISO) can be recorded. The snapshot repetition time is fixed at 500 μs, therefore the maximum resolvable Doppler frequency shift is 1000 Hz, corresponding to a maximum relative speed to be 186 km/h (51.67 m/s). Tab. I summarizes the main sounding parameters.

TABLE I
CHANNEL SOUNDER AND OBU-MK5 PARAMETERS

Channel Sounder

Parameter	Value
Configuration	SISO
Carrier frequency	5.8 GHz
Meas. Bandwidth	150 MHz
Snapshot Interval	500 μs
Transmit Power	27 dBm

OBU-MK5

Parameter	Value
Channel & freq.	178 - 5.89 GHz
Transmit Power	30 dBm
Transmission Rate	10 Hz
MCS	QBPSK-1/2
Packet length	400 Byte

2) Connectivity Tests: The TX and RX are both equipped with an OBU-MK5 transceiver, an external GPS server and a Hewlett-Packard HP CORE i5 laptop. The MK5-OBUs are manufactured by the Australian company Cohda Wireless, a leader in design and development of applications in vehicle communication [26]. The laptop is used for the management and configuration of the MK5-OBU transceiver through an SSH connection, as well as for storing all the data recorded in the microSD card of the MK5-OBU. While the MK5-OBU implements the full WAVE stack as well as the ITS-G5 [27].

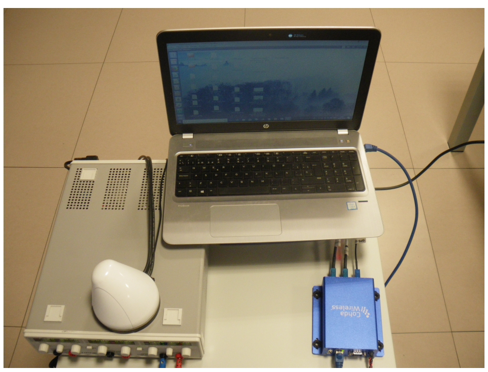

Fig. 4. Measurement Equipment from the transmitter side.

In addition, the OBU-MK5 transceiver has a custom physical layer according to the standard, and it offers a development kit that allows users to test their own applications and custom systems. A blue Ethernet cable as shown in the figure connects both devices.

The MK5 has GNSS capabilities which provide accurate information about the position and speed of the unit. The GPS signal is taken from an external rubidium clock by means of a micro-USB connector. The MK5 has three Fakra connectors for antennas, one for the GNSS antenna (this is not used because an external GNSS reference is taken) and the other two for dipoles antennas (5 dBi of gain) in the 5-6 GHz band used for the transmission of the connectivity test signals. The unused antenna connectors are connected to a 50 Ohm male SMA termination.

The OBU-MK5 transceivers offer a great flexibility regarding the configuration of their transmission parameters according to the standard. The parameters that can be modified are, among others: the transmission power, the modulation coding scheme (MCS), payload length of the frame, transmission rate, channel frequency, transmit antenna, or type of diversity. In addition, each OBU-MK5 transceiver records the statistics of a set of important parameters such as the received power, speed, time stamp, geographic position among others, from which different metrics can be estimated. The OBU-MK5s are initially configured as listed in Tab. I.

B. Planning

The channel sounding, and connectivity tests are carried out in two phases. First, the two measurement campaigns are conducted in a totally controlled environment using regular passenger cars to test the equipment and measurement protocols. In the second phase, the measurements are conducted in a more realistic test field, where the vehicles are passenger trains.

This paper considers a **V2I communication scenario**. For this T2T approach two vehicles are needed. Three phases are measured corresponding to the three maneuvers involved in the smart composition train use case: Coupling-Composition-Uncoupling.

Several driving speeds and distances are tested for this scenario. The particularities of the two measurement campaigns are described in the following:

1) Channel sounding: The first channel sounding measurements are conducted in July 2018 near Vienna, Austria. For that, a road running along a railway track for about 300m in a rural environment is selected. Fig. 5 shows the test site for the first phase of channel sounding.

Fig. 5. Test site for first phase channel sounding, (GoogleMaps).

2) Connectivity tests: The first connectivity test measurements are conducted also in July 2018 in the outside of Mondragon, Spain. For that, a closed road track around of the Mondragon University is selected (blue point in Fig. 6) in a rural controlled environment with a low traffic, to carry out the first phase of connectivity test.

Fig. 6. - Test site for first phase connectivity test (Googlemaps).

Then, the following metric set is expected to be analyzed, which reflects the performance of IEEE 802.11p in this stage:

- Transmission Power Test: The configuration parameters of Tab. I are maintained exerting the transmission power, which is varied between 20 and 30 dBm.
- Packet Length Test: The payload length is varied by 50, 150, 400 and 1500 Byte.
- Transmission rate Test: The packet transmission rate is varied by 10, 50 and 100 Hz.
- MCS Test: The MCS is varied in BPSK-1/2, QPSK-1/2, 16QAM-3/4 and 64QAM-3/4 Each of the tests lasts approximately 30 to 40 minutes, taking a short time to change of test.

C. Performance Indicators

To analyze the collected data, each set of measurements is evaluated using different performance indicators.

1) Channel sounding: The performance indicators used for the channel sounding data are the power delay profile (PDP) and the Doppler spectral density (DSD) metrics. These, together with a closer analysis of the environmental geometry, provide us with information about the main components influencing the radio channel, as well as the non-stationarities of the underlying fading process. The PDP and the DSD are derived from the local scattering function (LSF), which was introduced in [24], [25], and allows for a power distribution analysis of a non-stationary fading process. The estimation of the LSF uses a discretized version of the recorded channel transfer function $H[m, q]$, where m is the discrete time index and q is the discrete frequency index. In order to estimate the LSF, a stationarity region of 40 ms (M=80 samples) and the whole bandwidth of 150 MHz (N=601 samples) is defined. With these values, a resolution of 50 Hz and 6.67 ns in the Doppler shift and the delay domain is achieved, respectively.

The estimated time-varying PDP is then calculated as $\widehat{PDP}[k; n] = \sum_{p=-M/2}^{M/2-1} \widehat{LSF}[k; p, n]$, and the estimated time-varying DSD is calculated as $\widehat{DSD}[k; p] = \sum_{n=0}^{N-1} \widehat{LSF}[k; p, n]$, where p and n are the indexes in the Doppler shift and delay domain respectively; and k is the index of the stationarity region in time.

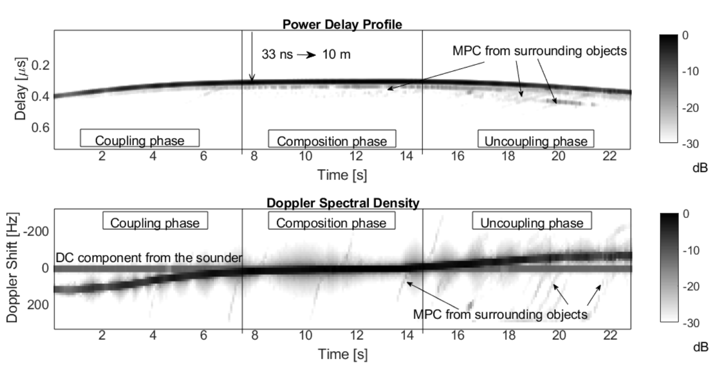

Fig. 7. Normalized PDP and DSD.

In Fig. 7 we plot the normalized PDP and the DSD for an exemplary measurement run. We can identify very clearly these three phases. During Coupling (0-7.4 s), the rear vehicle approaches the front vehicle until reaching a minimum safety distance: in the PDP the delay of the line of sight decreases until 33 ns; in the DSD the positive Doppler shift decreases from 125 Hz ($v_{rel} = 23.3$ km/h) to 0 Hz. During Composition (7.4-14.7 s), the two vehicles drive with constant distance: the delay and Doppler shift remain constant. And during Uncoupling (14.7-22.9 s), the rear vehicle increases the distance with the front one: the delay increases and the Doppler shift turns negative up to -75 Hz ($v_{rel} = 14$ km/h). We want to remark that the results presented in this paper are carried out with cars, not trains, and due to the limitations of the measurement site (only 300 m of a local road), we considered low driving speeds (up to 40 km/h).

2) Connectivity tests: In Fig. 8 the results of the IEEE 802.11p for a similar setup as the aforementioned (300 m of a local road, speeds up to 40 km/h) are shown. Three phases for T2T Scenario are also depicted.

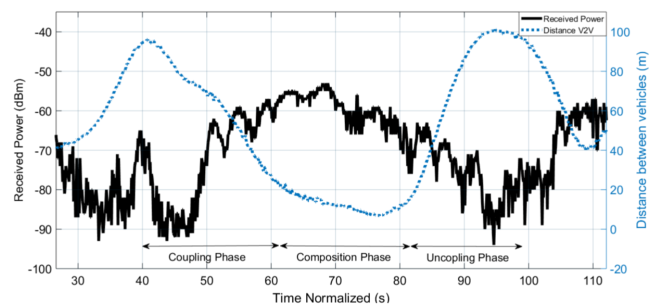

Fig. 8. CCDF of the MAC-to-MAC Delay.

Several indicators are selected in order to evaluate the connectivity performance of ITS-G5 in T2T communications: Update Delay, MAC-to-MAC Delay, Packet Error Rate (PER), and Throughput.

Fig. 9 shows results for the complementary cumulative distribution function (CCDF) is used for the analysis of the MAC-to-MAC Delay. The CCDF which expresses the probability that a given metric value exceeds a given reference value. The MAC-to-MAC Delay is the time elapsing from packet generation at the MAC layer of the TX until it arrives at the MAC layer of the RX. The MAC-to-MAC Delay is a relevant indicator for dynamic train coupling because it has accounts for other delay metrics, for example: processing delay, queuing delay, contention delay, propagation delay, and packet transmission time. This performance indicator reflects the reliability of a transmission in terms of delay, for example, in terms of percentage how many of all broadcasted packets have arrived within a certain deadline.

The results of the MAC-to-MAC delay under the STCC paradigm are shown at Fig. 9. Baseline is the result obtained with the reference configuration presented in Tab. I. The results obtained from the delay are aligned to those required by 3GPP

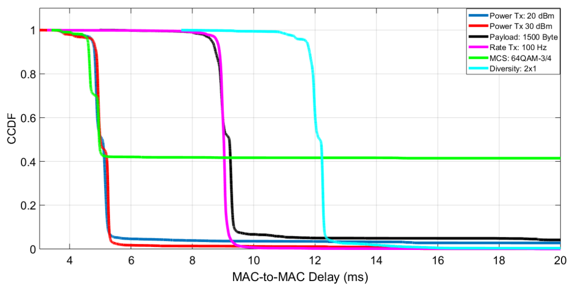

Fig. 9. CCDF of the MAC-to-MAC Delay.

[23], where states that the delay must be in the order of tens of milliseconds. The performance of IEEE802.11p/ITS-G5 more robust MCS configurations show that less than 4% of the transmissions have a greater delay than 14 ms at the receiver. Only when using the least robust MCS (64QAM-3/4) the system performance falls below the requisites. Additionally the impact of packet length is also evaluated, and the delay is approximately double when transmitting packages of the longest duration. Same happens when increasing the transmission rate. Still, 20 ms fall within the order of tens of milliseconds. And finally the effect of diversity is also analyzed, and results show that the use of diversity techniques increases the delay, which must be taken into account in security-related applications.

V. Conclusions

We have very clearly identified the three phases of a smart composition train maneuver (coupling-composition-uncoupling) and tested the viability of a more extensive measurement campaign under more realistic conditions.

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